THE EARTH INDUCTOR COMPASS.[1]

By PAUL R. HEYL and LYMAN J. BRIGGS.

(Read April 22, 1922.)

The instrument and accessories described in this memoir have been developed with especial reference to use in vessels for the navigation of the air. Navigating conditions in aircraft are such that little or no reliance can be placed on the indications of the ordinary magnetic compass. For this there are two principal reasons.

Lack of space in airplanes forces the pilot and his instrument board to be located in a region of considerable magnetic disturbance, due to the proximity of the engine and other magnetic bodies. Occasionally these are variable, such as the steering rod, which in some planes is of steel. Compensation, after the manner familiar to navigators of the water, is not always a satisfactory solution of the difficulty. Apart from the variable disturbing elements above referred to, the magnetism of the engine may change considerably during a long flight. On the U. S. Army airway from Dayton, Ohio, to Washington, D. C., it has happened that the compass has developed an error of as much as forty degrees before the trip was completed. In the endeavor to eliminate such troubles the compass is sometimes placed in the rear portion of the plane, and readings taken by devices more or less complicated, as in the German Bamberg compass. Such a plan, however, does not eliminate the second and more serious cause of disturbances.

The accelerations of an airplane are greatly in excess of those to be found in a water vessel; and the directive force of the earth's field on the magnetic needle is weak. Due to the great acceleration, the weak directive force, and the necessary inertia of the needle and card, the magnetic compass possesses rather a long memory for disturb-

[1] A memoir to which the Magellanic Premium was awarded January 6, 1922, by the American Philosophical Society.

ances to which it has been subjected. It is not difficult to give the plane such a motion as to set the compass card spinning on its pivot so that before its motion subsides sufficiently to allow of even an approximate reading the plane has traveled two or three miles. The great speed of the plane (ordinarily from seventy to one hundred miles an hour) and the comparatively sharp and sudden turns sometimes executed produce a set of conditions of an order entirely different from those to which a navigator of the water is accustomed. The attempt to meet these disturbances by damping the compass card is not a satisfactory solution; for damping, while it diminishes disturbance, also decreases sensitivity, none too great at best.

The difficulty of the situation is perhaps best shown by the fact that the Great War, which produced, under stress of necessity, so many inventions, closed without having brought out any satisfactory form of airplane compass on either side of the conflict.

For satisfactory service under conditions of this nature the earth inductor in connection with a galvanometer possesses a fundamental advantage over the magnetic needle. Unlike the latter, it has no memory. From instant to instant it furnishes an electromotive force determined by its orientation with respect to the earth's field, irrespective of its past or present state of translatory motion. This advantage has not been unrecognized by previous workers (Dunoyer: British Patent 4609 of 1907; Chabot: British Patent 9912 of 1903; Bliss: U. S. Patent 1,047,157 of Dec. 17, 1912). It may be noted that no one of these proposed devices possessed sufficient practicability to bring it into use during the war.

In all previous attempts at the construction of a compass of this type, the current developed in the rotating coil, amplified if necessary, was caused to pass through a galvanometer, and the course of the vessel indicated by the amount of deflection produced. The instrument described in the present memoir differs from all previous attempts in the following respects:

1. It employs a null method for its indications, and therefore enjoys all the advantages of sensitivity characteristic of null methods as a class. As long as the vessel lies in the course predetermined by the pilot, no deflection is produced in the galvanometer.

2. A course-setting device of a novel type is employed. By turning a movable dial carrying compass graduations to the desired course-mark, the electrical connection of the galvanometer to the earth inductor is so arranged that the galvanometer will read zero only when the vessel is in the desired line. This device enables the pilot to control a compass situated at a safe distance from magnetic disturbances without the use of a moving mechanical connection.

3. This course-setting device possesses a feature which enables the pilot to distinguish between north and south, or, in general, between the two opposite directions which the vessel may take in any line.

4. A method is provided for eliminating the errors due to rolling and pitching, arising from the vertical component of the earth's field.

5. By the judicious use of iron in the core of the coil, the size of the earth inductor may be greatly reduced and the current output increased without the introduction of any sensible error.

In the course of its development this instrument has naturally passed through several forms. Only the final form will here be described.

Current is generated by the rotation in the earth's horizontal field of an armature rotating about a vertical axis. A commutator and four collecting brushes, spaced at 90°, take off current from the armature. For simplicity we may first suppose the vessel to lie in the magnetic meridian. The brush system as a whole may then be turned to such a position that one pair of brushes furnishes no electromotive force and the other pair a maximum. The brush system may now be fixed in this position with respect to the vessel. If now the vessel be turned through an angle θ from the meridian, the two pairs of brushes will furnish electromotive forces proportional respectively to $\sin \theta$ and $\cos \theta$. In this it is assumed that θ is measured positively in a clockwise direction from the meridian, and that the commutator connections are so made that the algebraic sign of the voltage at each pair of brushes will be that proper for the sine or cosine of the angle in whatever quadrant that angle may be located. For this reason the two pairs of brushes will be henceforth referred to as the sine and cosine brushes, respectively.

If the sine brushes only are connected to the galvanometer, its reading will be zero only when the vessel lies in the magnetic meridian; and if the cosine brushes only are connected, the reading will be zero only in a magnetic east and west line.

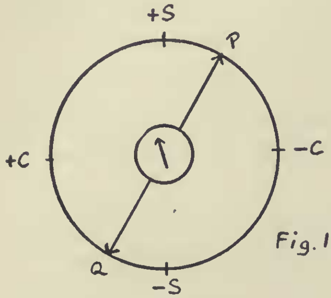


Fig. 1.

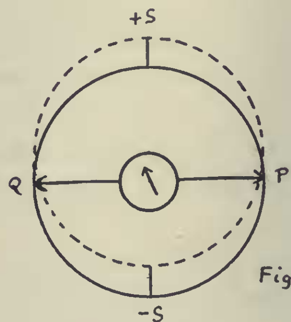


Fig. 2

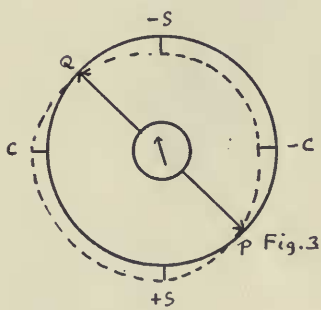


Fig. 3

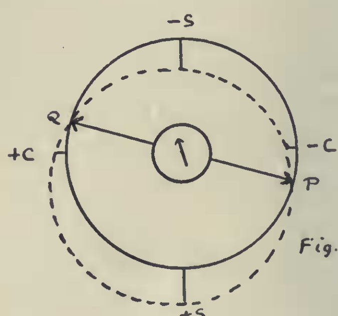


Fig. 4.

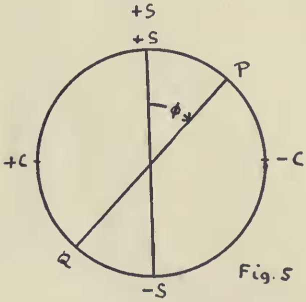


Fig. 5

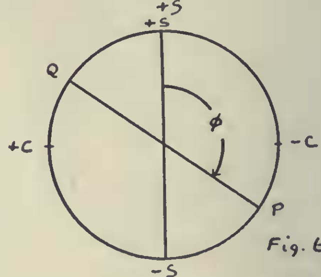


Fig. 6

We may connect the two pairs of brushes in series so that the voltage applied to the galvanometer is $\sin\theta + \cos\theta$. This function will be zero only when $\theta = 135°$ or $-45°$; that is, when the vessel lies in a northwest and southeast line. And if we use the combination $\sin\theta - \cos\theta$, this will be zero when $\theta = 45°$ or $225°$; that is, in a northeast and southwest line.

In general, since

$$m \sin \theta + n \cos \theta = 0$$

if $\tan \theta = -(n/m)$, the galvanometer reading may be made zero in

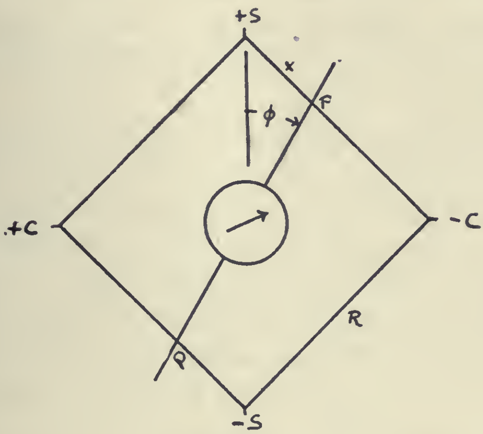


Fig. 7

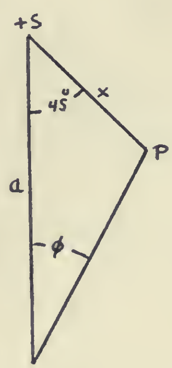


Fig. 8

any desired direction by combining, additively or subtractively, suitable fractions or multiples of the voltages from the two pairs of brushes. This is the underlying principle of the course-setting device known as the dial switchboard, which is an important part of this invention.

Such a switchboard may assume various forms. The form adopted in practice is very simple in actual construction, although not so simple in mathematical theory as certain more complicated practical forms that preceded it in the course of its development. Its theory is illustrated in Figs. 1–8.

In Fig. 1 we have a closed circuit of resistance, the sine and cosine voltages being connected to the circle at four equally spaced points $\pm S$, $\pm C$. The galvanometer connections are made at any two diametrically opposite points P, Q, of the circle. Indicating, as in Fig. 2, positive potential by a line drawn radially outward from the resistance circle, and negative potential by a line drawn inward, and supposing the vessel to lie in an east and west line, so that the sine voltage is a maximum and the cosine voltage zero, we have a distribution of potential around the circle indicated by the dotted line. The only diametrically opposite points which will be at equal potentials are those at the ends of the horizontal diameter. This, then, will be the null position for an east and west course.

If, on the other hand, the sine voltage is zero and the cosine voltage a maximum, as is the case in a north-south course, the null position will be that of the vertical diameter.

If the vessel lies in a northwest and southeast line, $\theta = -45^\circ$ (or 135°), sin θ is negative and cos θ positive, both, however, being equal in absolute numerical value. Maintaining the connections shown in Fig. 1, but changing the sign of S, the distribution of potential will be as shown in Fig. 3. Points $+S$ and $+C$ are at equal potentials; between them we have a level of potential, and no current flows in this quadrant. The same is true of the quadrant between $-S$ and $-C$. But between $+S$ and $-C$ (and $+C$ and $-S$) a fall of potential exists. Symmetry indicates that the only equipotential points for the galvanometer leads lie on a line making -45° with the vertical diameter; that is, pointing northwest with reference to the cardinal points previously determined (Fig. 2).

Let the vessel now veer a little farther to the west; the sine voltage will increase (negatively) and the cosine voltage decrease (positively). Fig. 4 represents the distribution of potential in this case. The potentials at $+S$ and $+C$ are no longer equal, that at $+S$ being greater than that at $+C$. In consequence, the line of contact will be shifted, as it should be, a little nearer to the horizontal than in Fig. 3.

It is a curious fact that in general the angle of the null contact line with the $\pm S$ line is not always equal to the course-angle θ of the vessel with the magnetic meridian. There is, as we have just seen, perfect correspondence at the cardinal and 45° points; but for points within each octant, as in Fig. 4, there is a departure rising to a maximum of about 4° near, but not at, the center of each octant, as the general mathematical theory will show.

Assume the S and C voltages applied as in Fig. 5 (same as Fig. 1) and let the contact line of the galvanometer be inclined at an angle ϕ to the $\pm S$ line, measured positively in the clockwise direction. We shall first suppose ϕ limited to the first quadrant.

$$\text{Potential at } P = \left(\frac{90^\circ - \phi}{90^\circ}\right)\sin\theta - \left(\frac{\phi}{90^\circ}\right)\cos\theta,$$

$$\text{Potential at } Q = -\left(\frac{90^\circ - \phi}{90^\circ}\right)\sin\theta + \left(\frac{\phi}{90^\circ}\right)\cos\theta.$$

If these are equal, we must have

$$\tan\theta = \frac{\phi}{90^\circ - \phi}. \tag{1}$$

Since equation (1) is algebraic in ϕ and transcendental in θ, it is evident that no linear relation can exist between ϕ and θ. Solving for ϕ we have

$$\phi = \frac{\pi}{2}\frac{\tan\theta}{1 + \tan\theta} = \frac{\pi}{2}\frac{\sin\theta}{\sin\theta + \cos\theta}. \tag{2}$$

Now

$$\phi - \theta = \frac{\pi}{2}\frac{\sin\theta}{\sin\theta + \cos\theta} - \theta, \tag{3}$$

which will be a maximum or minimum where

$$\frac{d(\phi - \theta)}{d\theta} = \frac{\pi}{2}\frac{1}{(\sin\theta + \cos\theta)^2} - 1 = 0. \tag{4}$$

The approximate first quadrant roots of (4) are 17° 24′ and 72° 36′ instead of the mid-points of the octants 22° 30′ and 67° 30′. At these roots the value of $\phi - \theta$ is nearly 4°, as shown in the following table.

ϑ.	ϕ.	ϕ-ϑ.
17° 24′	21° 28′	4° 4′
22° 30′	26° 22′	3° 52′
45°	45°	0
67° 30′	63° 38′	−3° 52′
72° 36′	68° 32′	−4° 4′
90°	90°	0

If ϕ lies in the second quadrant (Fig. 6), we have

$$\text{Potential at } P = -\left(\frac{\phi - 90^\circ}{90^\circ}\right)\sin\theta - \left(\frac{180^\circ - \phi}{90^\circ}\right)\cos\theta,$$

$$\text{Potential at } Q = \left(\frac{\phi - 90^\circ}{90^\circ}\right)\sin\theta + \left(\frac{180^\circ - \phi}{90^\circ}\right)\cos\theta.$$

If these are equal, we have

$$\tan\theta = -\frac{180^\circ - \phi}{\phi - 90^\circ}$$

$$\phi = \frac{\pi}{2}\frac{2 - \tan\theta}{1 - \tan\theta} = \frac{\pi}{2}\frac{2\cos\theta - \sin\theta}{\cos\theta - \sin\theta}. \tag{5}$$

The maximum and minimum values of $\phi - \theta$ in this quadrant are approximately at $\theta = 107^\circ\ 24'$ and $162^\circ\ 36'$. The values of $\phi - \theta$ at these points are 4° 4′ as in the first quadrant.

We may now obtain by computation from (2) and (5) the values of ϕ previously indicated by symmetrical considerations.

If, as in Fig. 2, $\cos\theta = 0$ and ϕ is in the first or second quadrant, both formulas give $\phi = \pi/2$.

If, as in Fig. 3, $\sin\theta = -(\sqrt{2}/2)$, $\cos\theta = \sqrt{2}/2$ and ϕ is in the second quadrant, formula (5) gives

$$\phi = \frac{\pi}{2}\frac{3}{2} = 135^\circ.$$

To avoid in practical construction the non-uniform distribution of resistance around a circle which would be necessary to give a uniformly graduated dial, it is sufficient to replace the circle by a square, as indicated in Fig. 7. Contact of the galvanometer leads is made at points P and Q, whose distances from the center of the square vary with the angle of setting. It may readily be seen that the resistance included between $+S$ and P will vary more rapidly per unit angle of turn near the corner of the square than at the middle of a side.

In Fig. 8, a is a constant and x a variable side of the triangle having a constant angle 45° and a variable angle ϕ. In this triangle the points P and $+S$ correspond to the similarly lettered points in Fig. 7. In Fig. 8 we have:

$$\frac{x}{\sin\phi} = \frac{a}{\sin(135^\circ - \phi)} = \frac{a}{\sin(45^\circ + \phi)},$$

$$x = \frac{a\sin\phi}{\sin(45^\circ + \phi)}. \tag{6}$$

Now, in Fig. 7 let R be the length of one side of the square; then, if ϕ be in the first quadrant:

$$\text{Potential at } P = \left(\frac{R - x}{R}\right)\sin\theta - \left(\frac{x}{R}\right)\cos\theta,$$

$$\text{Potential at } Q = -\left(\frac{R - x}{R}\right)\sin\theta + \left(\frac{x}{R}\right)\cos\theta.$$

If these are equal,

$$\tan\theta = \frac{x}{R - x}$$

$$x = R\frac{\tan\theta}{1 + \tan\theta} = R\frac{\sin\theta}{\sin\theta + \cos\theta}. \tag{7}$$

Substituting in (7) the value of x from (6) and noting that $a = (R\sqrt{2})/2$, since R is the side of the square of which a is the semi-diagonal, we have:

$$\frac{\sqrt{2}}{2}\frac{\sin\phi}{\sin(45^\circ + \phi)} = \frac{\sin\theta}{\sin\theta + \cos\theta}. \tag{8}$$

(8) expresses, for a square frame, the relation between the course-angle θ of the vessel and the null contact angle ϕ of the dial switch-board. (8) reduces as follows:

$$\frac{\sqrt{2}}{2}\frac{\sin\phi}{\sin(45^\circ + \phi)} = \frac{\sqrt{2}}{2}\frac{\sin\phi}{\sin 45^\circ\cos\phi + \cos 45^\circ\sin\phi}$$

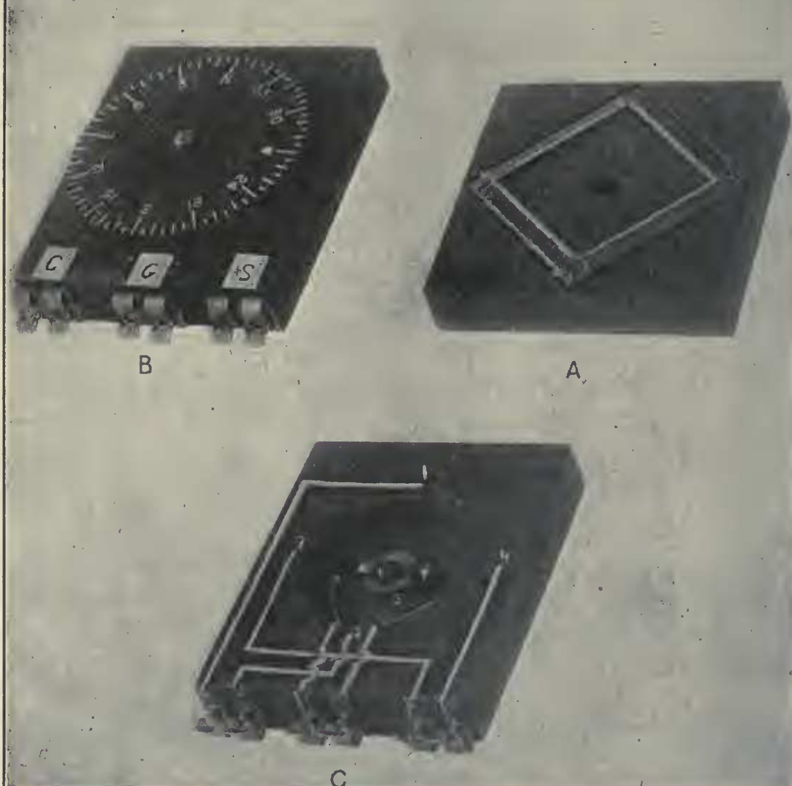
$$= \frac{\sin\phi}{\cos\phi + \sin\phi} = \frac{\sin\theta}{\sin\theta + \cos\theta}.$$

Which shows that for a square frame $\phi = \theta$, at least for the first quadrant. It may readily be shown that the same relation holds in the second quadrant as well, as indeed is indicated by conditions of symmetry.

Upon this theory may be based a very simple practical construction for the dial switchboard, illustrated in Fig. 9 (photograph).

Fig. 9*a* shows the switchboard base with dial removed, showing the square resistance frame. This frame has an inside diameter of

FIG. 9



6.5 cm. and each turn of wire is nearly 2 cm. long. It is wound with No. 30 constantan wire, and each arm has a resistance of about 37 ohms. The inner edge of the square frame stands slightly above the outer edge, and along this inner edge the insulation is removed from the turns of wire.

Fig. 9*b* shows the assembled switchboard, front view. The dial carrying the compass divisions carries on its under side the wiping contacts which constitute the terminals of the galvanometer connections. These contacts press against the exposed portions of the wire on the square frame.

Fig. 9*c* shows the back view of the switchboard. From the four corners of the square resistance frame wires run through holes *1, 2, 3, 4* to the back of the switchboard, and thence as indicated to the *S* and *C* binding posts, which in turn are connected respectively with the sine and cosine brushes. From the wiping contacts on the under side of the dial wires run through the hub *5*, which moves with the dial, to the wiping contacts *6, 7,* from which wires run to the posts *G*, which are connected with the galvanometer.

A simple manipulation of the dial switchboard enables the pilot to distinguish between north and south, or in general between the forward and backward directions in which he may be flying in any line when the galvanometer reads zero. If the dial be turned slightly, say to the right, the pointer of the galvanometer will move from zero; and the galvanometer connections can be made so that this motion will also be to the right when the vessel is moving forward on the course indicated by the initial position of the dial switchboard. If the plane be flying backward on this course, the flux through the armature is reversed in direction; and, with the same connections, the motion of the pointer will now be opposite to the motion of the dial.

Contrary to what might be supposed, there is no difficulty in obtaining a galvanometer at once sufficiently sensitive and rugged to be used under the conditions prevailing in an airplane. The galvanometer used is of a standard commercial type, double-pivot spring construction, giving one millimeter deflection for one hundredth of a milliampere. Its resistance is about 22 ohms. Being always in circuit with a resistance less than its critical damping resistance, the motion of its pointer is always dead-beat. The vibration and jarring to which the instrument is subjected in flight are not great, being actually less than are to be found at the instrument board of an automobile, where instruments of this and similar types are frequently installed.

The earth inductor itself is shown in Fig. 10 (photograph). It is installed in the fuselage, behind the second seat. The supporting board *1* runs athwart the ship and is clamped to the upper wooden

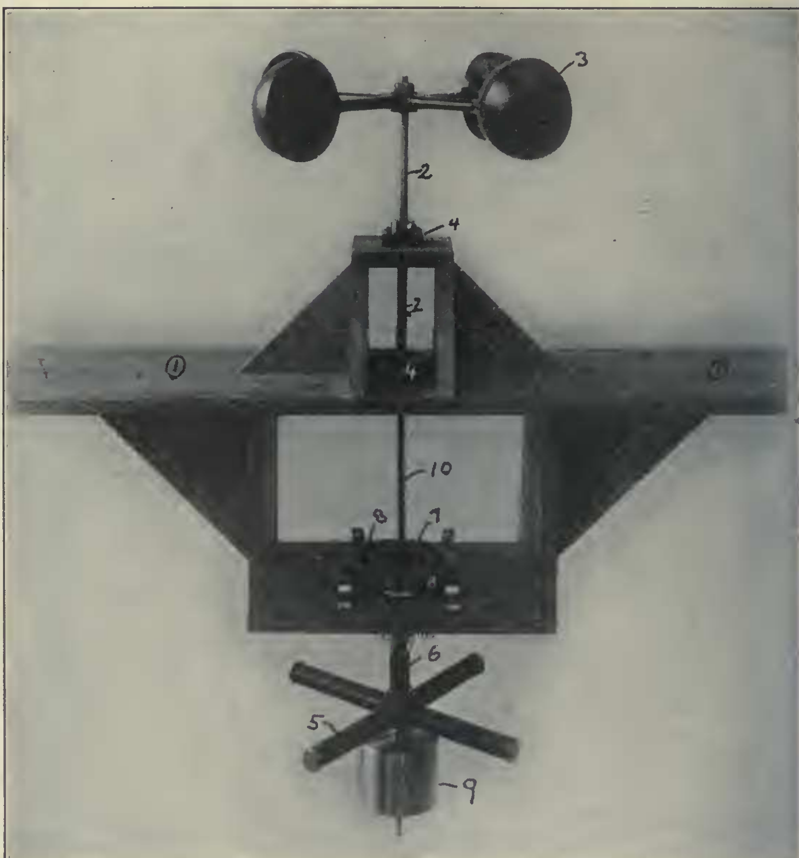


FIG. 10

members (longerons). Through the upper fabric of the fuselage (the turtle back) projects the driving axle *2* bearing the four-cup propeller *3*. This axle runs in ball bearings *4* of the self-aligning type. The axle *2* is joined to the axle *6* by a short piece of flexible shaft *10*.

A decided novelty is introduced in this invention in the use of an iron core in the armature. For an iron-cored armature revolving in the earth's field the conditions differ in one important respect from those obtaining in the dynamo; in the earth's field we must reckon with free poles in the armature, and a consequent self-demagnetizing effect. This effect is a minimum if the iron is in the form of a rod long as compared to its diameter. This leads to a cross-shaped armature *5*, as shown in the photograph. The arms are of 3½ per cent. silicon steel, which has, in a field equal to the earth's horizontal component, a permeability of about four times that of ordinary soft iron. The residual magnetism is also considerably less. The four arms of the cross are carried by a central hub of the same material. The arms are 1 cm. in diameter, and measure 20 cm. from end to end of a pair of opposite arms. For a rod of these proportions the demagnetizing coefficient is small enough to allow a permeability of about ten times that of a cube of the same material.

Upon each of the four arms there are 500 turns of No. 20 B. & S. copper wire, silk enamel insulation. The winding is of the closed coil type, with a four-segment commutator. The total resistance of the wire on all four arms is 3.2 ohms, and the resistance through a pair of opposite commutator segments 0.8 ohm. At 20 revolutions per second, the electromotive force is 8 millivolts.

The armature and commutator are carried by the axle *6*, which runs in a thrust ball bearing mounted in the gimbal rings *7*. There are four collecting brushes of carbon, spaced 90° apart, on a mounting which swings with the axle and commutator. By turning the whole gimbal system by means of the slots and screws *8* the brush system can be set at any desired angle with respect to the vessel in which it is installed. The resistance of the armature through a pair of brushes is from 1 to 1.5 ohms.

Below the armature *5* is a brass weight *9*, weighing about a kilogram. The length of the pendulum thus formed is short enough to give a time of (half) swing of about one third of a second. The bearings for the gimbal rings *7* are provided with leather friction washers, by tightening which any desired degree of damping may be applied. It is usual to damp the pendulum so that it will execute from six to eight half-swings before coming to rest after a displacement of about 20°, occupying from two to three seconds in the process. This allows sufficient looseness to permit response to a small angle of tilt, and also sufficient damping to insure that the oscillations do not continue beyond the time required for the plane to regain its level.

On rounding a curve centrifugal force will, of course, deflect the pendulum somewhat from the vertical; but such centrifugal force is removed as gradually as it is applied, and by the time the plane comes again into a straight course the axis is stationary in a vertical position.

The natural time of swing of the armature pendulum as arranged is, as has been said, about one third of a second. The time of roll or pitch of even the smallest planes is several seconds, and for the larger planes still longer. The disturbances arising from the driving mechanism have a period of about one twentieth of a second. The pendulum is sufficiently massive to resist forced vibrations of the latter period; and the oscillations of the plane itself are too remote in period to produce any sensible effect. A certain amount of gyrostatic action at the usual speed of revolution (1,200 r. p. m.) contributes materially to the stabilizing action. Excess of gyrostatic action is undesirable, as its effect is to lengthen the period of swing and bring it too near that of the oscillations of the plane.

Actual experiment is necessary to appreciate the very satisfactory degree of stability possible of attainment by an apparatus of this nature.

It might be supposed that there would be a small quadrantal error in an electrical system such as described, due to the fact that the armature is sending out a current which is not constant for different azimuths of the vessel, and consequently the reaction of the armature on the earth's field would be variable. When one set of brushes alone is functioning the electromotive force E is applied to opposite corners of the square frame (Fig. 7). If R be the resistance of one arm of the frame, the equivalent resistance of the whole frame is also R, and the current output of the armature is $E/(R+r)$, where r is the internal resistance of the armature. If, as in Fig. 3, both pairs of brushes are equally active, the voltage of each pair is $0.7E$. The resistance in the square frame encountered by each voltage is that of one quadrant, or R; hence the total current coming from the armature is $1.4E/(R+r)$.

Laboratory tests fail to show such an error, which, in fact, is non-existent. Though the current output of the armature varies, the distribution of the current in the armature varies also, so that its

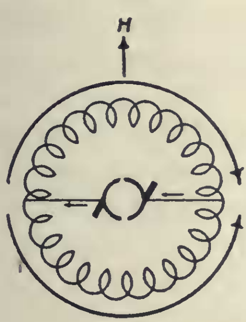


Fig. 11

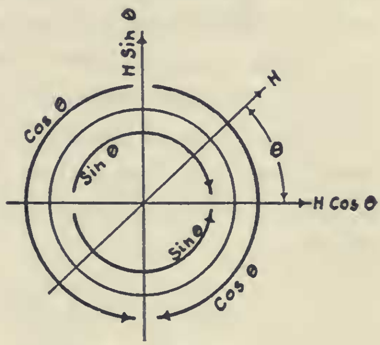


Fig. 12

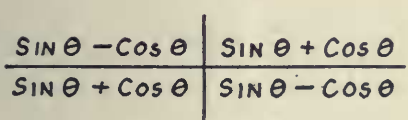


Fig. 13

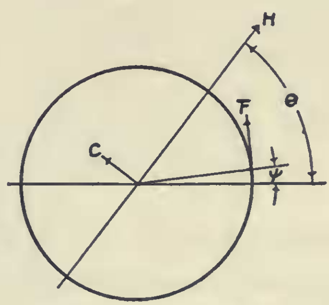


Fig. 14

integrated cross-field reaction is constant. This is readily shown by considering the case of a Gramme ring, of which the compass armature is a special and degenerate case.

Fig. 11 represents such a ring, H being the direction of the earth's field. Current will flow as shown by the arrows, producing a cross-field horizontally directed.

If the field be inclined at an angle θ to the horizontal, as in Fig. 12, we may resolve it into two components, $H \sin \theta$ vertically and $H \cos \theta$ horizontally. If the intensity of the currents in each half of the ring in Fig. 11 be taken as unity, the intensities of the similar currents generated in Fig. 12 will be $\sin \theta$ and $\cos \theta$, respectively. These currents are taken off by two pairs of brushes, and encounter the same external resistance in the dial switchboard. We may consider these component currents as superposed, the intensities in the four quadrants being shown in Fig. 13.

Let the radius of the ring be unity and let L be the inductance per unit arc of the ring. Then, representing the current intensity at any angle ψ (Fig. 14) by i, the total cross-field C will be proportional to

$$2L\int_0^{\pi} i \cos (\theta - \psi) d\psi$$

where $\theta - \psi$ is the angle between the reaction-field of the element of the ring at ψ and the perpendicular C to the field H.

Using the values of i in Fig. 13 this integral breaks up into two.

$$\begin{aligned} 2L (\sin \theta + \cos \theta) \int_0^{\frac{\pi}{2}} \cos (\theta - \psi) d\psi \\ + 2L (\sin \theta - \cos \theta) \int_{\frac{\pi}{2}}^{\pi} \cos (\theta - \psi) d\psi \\ = 2L \left[(\sin \theta + \cos \theta)^2 + (\sin \theta - \cos \theta)^2 \right] \\ = 4L. \end{aligned}$$

Hence, the resultant cross-field reaction of the ring is independent of the course-angle θ, and there is no quadrantal or other segmental error from this source.

The instrument as above described will give about one millimeter deflection at the galvanometer for five degrees change of course, the sensitivity being a little greater at the cardinal points than in the middle of a quadrant. This sensitivity is capable of a reasonable amount of increase, if desired, by using a larger armature with a greater number of turns, or by increasing the speed of rotation, but for the present state of the art of aërial navigation the instrument is sufficiently sensitive.

The total weight of the apparatus as shown in Fig. 10 is about five and a half (5½) kilograms.

Excessive tilt is prevented by a guard ring (not shown in Fig. 10) supported by guy wires in such a position as to intercept the motion of the lower projecting end of the axle *6* when the angle of tilt exceeds 20°, an angle not usually reached in ordinary flying. The great demand for a compass comes from cross-country and cloud-flying—not from acrobatic maneuvers.

Air tests of this instrument have been made during its development at one of the flying fields in this country, the latest series being completed during the week of October 24, 1921. This last series of tests has demonstrated that the instrument as here described is reliable in the air; that the needle of the galvanometer can be read during pitching to a half millimeter, corresponding to two and one half (2½) degrees change of course. It appears to be impossible for a pilot to roll his plane without also slightly veering it sufficiently to cause an oscillation of the needle of about one (1) millimeter on either side. The needle is unaffected by a vertical drop or "bump." On rounding a curve centrifugal force deflects the needle; but such force diminishes, on leveling up, at a rate sufficiently slow to allow the damped pendulum to become stationary by the time it reaches the vertical. A sharp veer of the plane will cause a slight oscillation of the needle, which is damped out in about three (3) seconds. Due to the constant slight vibration of the plane, the damping of the pendulum produces no loss of sensitivity, the pendulum being shaken into the vertical from even a small displacement.

In the opinion of those pilots who have tested the instrument some form of electrical drive would be preferable to wind power, as affording a higher speed and greater sensitivity, and being more uniform. Many planes carry electrical generators. No disturbance of the compass would arise from the rotating field of an A.C. motor mounted on the same axle, as the flux due to the stray field would rotate at the same speed as the earth inductor, and be therefore invariable with respect to the coil.

Certain mechanical improvements in detail have been shown by the latest air tests to be advisable. An invention, like a work of art, is never finished. Metallic brushes will probably be preferable to carbon for a long flight; and a commutator of hardened steel will probably save frequent replacements. The question of brush wear is naturally more important at eight (8) millivolts than at ordinary commercial pressures.

Addenda.

Since the date of the presentation of the foregoing memoir certain additional and correctional material has accumulated.

A comparative examination of various forms of commutator and brushes has shown that a mica-filled brass commutator and brushes of carbon are by far the most satisfactory combination. Such an arrangement has been run in the laboratory at 20 revolutions per second for 146 consecutive hours with a variation of less than one degree in the compass reading at any time during the test. The wear on the brushes was trifling. One hundred hours' flying is about the maximum service obtained from an airplane before complete overhauling of its engine is necessary. These additions have been incorporated in the text.

U. S. Bureau of Standards,
Washington, D. C.,
November, 1921.

"This instrument is a part of the programme set by the Air Service, in its attempt to put the navigation of the air on a basis as trustworthy as that of the water. The study of the problem was undertaken by the Bureau of Standards at the request of the Air Service, and the expense incident to the development of the final successful model was defrayed by Air Service funds. The flying tests were carried out with the coöperation of the Engineering Division of the Air Service at McCook Field, Dayton, Ohio."